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Towards the standardization of sequence stratigraphy – Reply to Discussion by William Helland-Hansen

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Rationale

We thank William Helland-Hansen for his compliments and feedback on our paper. We aimed to establish a consensus in sequence stratigraphy by using a neutral approach that focused on model-independent, fundamental concepts, because these are the ones common to various approaches. This search for common ground is what we meant by ‘standardization’, not the imposition of a strict, inflexible set of rules for the placement of sequence-stratigraphic surfaces. Our work is meant to eliminate the present state of methodological and nomenclatural confusion within sequence stratigraphy, which is largely the result of uncoordinated effort in the development of the method and the proliferation of terminology that is unnecessarily complex.

The model-independent (i.e., common to various approaches; Figs. 10 and 22 in Catuneanu et al., 2009) notions provide the practitioner with the ‘tools’ to identify the fundamental ‘building blocks’ in the rock record on the basis of observations of facies and/or stratal stacking patterns, in a generic manner that is independent of any specific sequence stratigraphic approach. The realization that the identification of these ‘building blocks’ (also referred to as ‘genetic units’ or ‘systems tracts’ in Catuneanu et al., 2009) is more important than the selection of where sequence boundaries should be placed in the construction of a sequence stratigraphic framework is the basic premise for reaching a consensus in sequence stratigraphy. This is because, in practice, the data often dictate which surfaces are best expressed and hold the greatest utility at defining sequence boundaries, so flexibility is required.

It should be noted that in the past, working groups appointed by the North American Commission on Stratigraphic Nomenclature and by the International Subcommission on Stratigraphic Classification (ISSC) had all failed to arrive at a consensus. Now, thanks to the publication of our paper, follow-up work mandated by the ISSC is underway. In no way is this standardization meant to be an obstacle that will limit further conceptual development or prevent certain approaches to specific situations, as feared by Helland-Hansen. In fact, the recognition of which concepts are fundamental and which are model-dependant (Figs. 10 and 22 in Catuneanu et al., 2009) may pave the way toward clearer thinking about sequence stratigraphy, which might in turn renew interest in this important approach to stratigraphic analysis. Whether or not sequence stratigraphy is mature enough for a common ground to be recognized will be revealed by future research. Experience shows that formalizing stratigraphic practices in codes and guides has not “frozen” their use and advancement.

Sequence stratigraphy beyond “coastal depositional environments”

The definition of a sequence that is used in our paper does not make reference to a base-level cycle, whether marine or lacustrine, and focuses instead on the more general cycles of change in accommodation or sediment supply, regardless of cause or depositional setting. Therefore, it is suited to broad application in all environments. Accommodation changes in an upstream-controlled fluvial setting, for example, may have nothing to do with changes in base level at the coastline, yet accommodation does change and creates sequences. Similarly, offshore sub-basin tectonism may also generate sequences in a manner that is independent of changes in base level at the coastline. The fact that such inland or offshore sequences may have no temporal

correlation with the base-level controlled sequences in the coastal area is important and needs to be appreciated.

Accommodation (and the factors that control it) may be environment-specific, so it is logical that there will be different sequences and types of systems tracts in each broad environmental setting. Evidently, the definition of 'conventional' sequence stratigraphic concepts that make reference to shoreline trajectories (e.g., forced regression, normal regression, transgression) do not apply to successions that form beyond the influence of base-level change at the coastline. However, 'unconventional' systems tracts may be defined instead (see discussions on 'conventional' versus 'unconventional' systems tracts in Catuneanu et al., 2009, p. 20, 22, 29).

As we did advocate an approach that was applicable to all depositional settings, the proposed model-independent workflow (Figs. 10 and 22 in Catuneanu et al., 2009) cannot be described as 'incomplete'. While a most detailed sequence stratigraphic framework may be constructed in a coastal area (Fig. 17 in Catuneanu et al., 2009), the application of sequence stratigraphy extends to all depositional settings, without necessitating a physical or genetic link to coastal systems.

Terminology

We appreciate the logic presented by Helland-Hansen in proposing the usage of his set of terms. It is possible that some of his terms are superior to the ones we recommended, and we will take them into consideration before the ongoing work for the ISSC is concluded. One solution might be to apply the principle of historical priority, which would give precedence to the original set of terms. We recognize, however, that precedence is not necessarily the best criterion for the selection of a standard set of terms. Newer terms, if shown to be better, should replace older terms, although experience shows that the replacement of well-established terms can be difficult even if they are no longer the preferred ones. Updates of stratigraphic codes and guides provide the practitioner with the latest developments in methodology and nomenclature.

It does need to be remembered that one goal at this stage in the process of 'standardization' is to eliminate confusion created by the proliferation of unnecessarily complex, and sometimes contradictory, terminology. We aimed at a selection of terms that are most intuitive and most commonly recognized by the practitioner. For example, maximum flooding surface is used and recognized widely within the stratigraphic community, and its replacement with a synonymous term such as the "maximum transgression surface" as proposed by Helland-Hansen, may not be helpful in any conceptual or practical way. Similarly, the terms normal regression (progradation with aggradation) and forced regression (progradation with downstepping) are equivalent with the terms ascending regression and descending regression, but the former are much more widely recognized and represented in the literature.

'Ideal' versus 'real' base-level cycles

In Helland-Hansen's definition, an 'ideal' base-level cycle is a cycle that includes both stages of rise and fall, in which the interplay of base-level change and sediment supply results in a predictable succession of 'conventional' systems tracts: highstand normal regressive – forced regressive – lowstand normal regressive – transgressive. The question is whether the use of such

an ‘ideal’ cycle as a norm for comparison is appropriate for the definition of a full *model-independent* approach.

The model-independence of the workflow that we proposed stems from the delineation of genetic units in the rock record, to the extent afforded by the available data, irrespective of the specific sequence stratigraphic approach (Fig. 22 in Catuneanu et al., 2009). This workflow is in no way linked to any assumptions regarding syn-depositional changes in base-level, or in accommodation in general. While we used ‘ideal’ cycles as an illustrative teaching tool to explain the formation of the entire variety of stratal stacking patterns and corresponding genetic units, we also made it clear that ‘cycles’ in the rock record are not necessarily ‘ideal’, symmetrical, or complete. We also state that “There are multiple combinations of what a sequence may preserve in terms of component genetic units (i.e., systems tracts), which is why no single template can provide a solution for every situation” (Catuneanu et al., 2009, p. 15).

Much of Helland-Hansen’s argument about a ‘standardized’ approach stifling creativity, as well as his dislike of the use of an ‘idealized’ cycle as a norm for comparison, are similar to the criticisms leveled at facies models. Conceptually, the use of an ‘ideal’ cycle as an illustration of sequence stratigraphic concepts is equivalent to the use of an upward-fining succession as a facies model for a meandering-river point bar. However, nobody would argue that every real-world point bar must match the idealized model for a point bar. Similarly, there is no expectation that real sequences should always match an ‘ideal’ accommodation cycle.

Sequence definition

The final point raised by Helland-Hansen questions the appropriateness of having “cyclicity as a prerequisite for sequence definition”, and hence the applicability of our proposed definition of a ‘stratigraphic sequence’ (i.e., “a succession of strata deposited during a full cycle of change in accommodation or sediment supply”; Catuneanu et al., 2009, p. 19) versus Mitchum’s (1977) definition of a ‘sequence’ as “a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities”.

All existing sequence stratigraphic schemes (Figs. 3 and 4 in Catuneanu et al., 2009) implicitly or explicitly incorporate a full cycle of change in accommodation or sediment supply in the definition of a sequence, because the beginning and the end of one cycle is marked by the same type of ‘event’: e.g., the onset of base-level fall; the onset of base-level rise; the end of regression; or the end of transgression. Consecutive ‘events’ of the same type must be of similar scale in order to define cycles of a specific hierarchical order (Johnson et al., 1985).

Mitchum’s (1977) definition presents two limitations. Firstly, his formulation is restrictive in the sense that it requires an unconformity at the sequence boundary. There are cases where genetic stratigraphic sequences or transgressive-regressive sequences *sensu* Johnson and Murphy (1984) are bounded entirely by conformable maximum flooding or maximum regressive surfaces respectively. Other similar situations have been acknowledged by Helland-Hansen in his discussion of alternating normal regressive – transgressive deposits without intervening stages of base-level fall.

Secondly, Mitchum's (1977) definition is more applicable to systems tracts rather than to sequences. This is because there are cases where sequences may include strata that are neither "relatively conformable" nor "genetically related" at the selected scale of observation. Where subaerial unconformities are present in a succession, they are included within genetic stratigraphic sequences that are bounded by maximum flooding surfaces. This could, in some cases, lead to the placement of *genetically unrelated strata* (from below and above the subaerial unconformity) within the same sequence. Depending on the development and placement of unconformities (e.g., the subaerial unconformity, or the unconformable portion of the maximum flooding surface) relative to the sequence boundaries, *all* types of sequences (depositional, genetic stratigraphic or transgressive-regressive) may include successions of strata that are *not relatively conformable*. However, whether unconformities are placed at the sequence boundary or within the sequence (i.e., at the systems tract boundary), a systems tract always includes a relatively conformable succession of genetically related strata at the selected scale of observation.

Conclusion

The flexibility afforded by a 'standard' model-independent workflow that lays emphasis on stratal stacking patterns (genetic units) and bounding surfaces in the rock record, rather than on the selection of any particular boundary-dependent model, eliminates the need for any predefined templates. As such, the practitioner should no longer feel the need to fulfill the predictions of any particular model. Each case study is different, and the sequence stratigraphic organization of the rock record varies greatly with the tectonic and depositional setting. The types of data available for analysis, as well as the scale of observation, also make a difference to what can be interpreted from the rock record. This immense variability underlines the value of defining a model-independent workflow. In spite of this variability, however, there are common elements between all stratigraphic sequences in the rock record, no matter how they are defined: they are all the product of changes in accommodation (whether fluvial or marine) or sediment supply and they all consist of a combination of the same basic 'building blocks' (i.e., 'conventional' or 'unconventional' systems tracts). The identification of these 'building blocks', without any expectations in terms of model predictions and templates, provides the key to the universal application of sequence stratigraphy.

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